

Merging White Dwarfs and Thermonuclear Supernovae

M. H. van Kerkwijk

*Department of Astronomy & Astrophysics, University of Toronto, 50 Saint George Street,
Toronto, ON, M5S 3H4, Canada; mhvk@astro.utoronto.ca*

Thermonuclear supernovae result when interaction with a companion reignites nuclear fusion in a carbon-oxygen white dwarf, causing a thermonuclear runaway, a catastrophic gain in pressure, and the disintegration of the whole white dwarf. It is usually thought that fusion is reignited in near-pycnonuclear conditions when the white dwarf approaches the Chandrasekhar mass. I briefly describe two long-standing problems faced by this scenario, and our suggestion that these supernovae instead result from mergers of carbon-oxygen white dwarfs, including those that produce sub-Chandrasekhar mass remnants. I then turn to possible observational tests, in particular those that test the absence or presence of electron captures during the burning.

Key words: binaries: close — supernovae: general — white dwarfs.

1. The Current Paradigm and Its Problems

A thermonuclear or type Ia supernova (SN Ia) is generally thought to be produced by a carbon-oxygen white dwarf that accretes matter relatively slowly, on timescales of $\gtrsim 10^6$ yr (limited by the rate at which heat from accretion and possible nuclear processing can be radiated, viz., the Eddington luminosity; for reviews, Nomoto *et al.* 1994; Hillebrandt & Niemeyer 2000). As the white dwarf accretes, its interior is heated, but it does not reach ignition, because at temperatures of $\gtrsim 10^8$ K, neutrino cooling becomes efficient enough to balance the heating (see Fig. 1). However, as the white dwarf approaches the Chandrasekhar mass, the density in its core becomes so high that fusion becomes possible at lower temperatures (in partly pycno-nuclear conditions; Fig. 1). Once this happens, a runaway ensues, stopping only when degeneracy is lifted and thermal pressure can expand and cool the region. The process triggers a burning front that proceeds through the white dwarf, generating the energy that eventually disrupts it.

The above is physically plausible, but it has two well-known problems. I briefly describe these below, before turning to our alternative.

(a) *The Paucity of Possible Progenitor Systems*

Over the age of the Universe, for every solar mass of stars formed, $\sim 0.0023 \pm 0.0006$ SN Ia seem to occur (Mannucci *et al.*, 2005; Maoz *et al.*, 2011). Since ~ 0.22 white dwarfs are expected for every solar mass formed (the remainder being in low-mass stars that are still alive), one infers that a surprisingly high fraction, of $\sim 1\%$, of all white dwarfs eventually produce SN Ia. Comparing different galaxies, the instantaneous SN Ia rate similarly seems to be $\sim 1\%$ of the white-dwarf formation rate (Pritchett *et al.*, 2008).

Most SN Ia models invoke “single degenerate” progenitors, in which a white dwarf accretes from a non-degenerate companion (Whelan & Iben, 1973). In principle, ample numbers of such binaries exist and several routes to explosions have been proposed (Iben, Jr. & Tutukov, 1984). No route, however, seems both common and efficient.

The main problem is that if mass transfer is slow, unstable hydrogen fusion in the accreting matter causes novae, which in most cases appear to remove as much mass as was accreted (Townsley & Bildsten 2004; though white dwarfs in cataclysmic variables are more massive than in their progenitors, Zorotovic *et al.* 2011). If accretion is faster, hydrogen burns stably, but only in a small range of accretion rate can expansion and mass loss be avoided (Nomoto *et al.* 2007; for the effect of helium flashes, see Iban *et al.* 2012). Empirically, the best-suited systems are the supersoft X-ray sources (Rappaport *et al.*, 1994), but those are far too rare to explain the SN Ia rates (Di Stefano, 2010a; Gilfanov & Bogdán, 2010). We may be missing systems, e.g., more rapidly accreting white dwarfs that expanded and hid from X-ray view (Hachisu *et al.*, 2010). However, for such sources – as for many single-degenerate channels – the lack of evidence for (entrained) hydrogen in SN Ia is surprising (unless the explosion can somehow be delayed, as in the “spin-up/down” model; Justham 2011; Di Stefano *et al.* 2011).

Another class of SN Ia models invoke “double degenerates,” where a white dwarf merges with another (Webbink, 1984; Iben, Jr. & Tutukov, 1984). As ignition is not expected during the merger (except perhaps for unusually massive, $\gtrsim 0.9 M_{\odot}$ white dwarfs, Pakmor *et al.* 2012), it is usually assumed an explosion will follow only if the combined mass exceeds the Chandrasekhar mass. This is rare, however, and both theoretical (Ruiter *et al.*, 2009; Mennekens *et al.*, 2010; van Kerkwijk *et al.*, 2010) and empirical (Badenes & Maoz, 2012) rate estimates fall well below the SN Ia rate. Furthermore, the observed number of supersoft symbiotic progenitors with the required massive white dwarfs is substantially smaller than that expected (Di Stefano, 2010b).

(b) The Difficulty of Reproducing SN Ia Properties

In degenerate matter, a thermonuclear runaway will proceed to completion unless degeneracy is lifted, and thermal pressure can expand and cool matter. After initial ignition, what happens depends on the conditions. For sufficiently high overpressure in a sufficiently large region (where what is “sufficient” remains to be understood; Seitzzahl *et al.* 2009), a detonation is triggered: a shock strong enough to cause neighbouring matter to ignite and burn in turn. Since a detonation proceeds supersonically, the white dwarf has no time to expand and the initial density everywhere determines the end-point of the runaway. For a near-Chandrasekhar mass white dwarf, most matter is at very high density and thus far too much ^{56}Ni is produced.

For a near-Chandrasekhar mass white dwarf, however, the energy release even from fusion up to ^{56}Ni does not lead to strong overpressure, and a deflagration is more likely, where neighbouring regions are ignited by a heat wave rather than a shock. Since a deflagration is sub-sonic, the white dwarf expands as the burning front progresses. Thus, burning takes place at lower density, reaching lower peak temperatures and producing less ^{56}Ni . Unfortunately, the burning front appears to be too slow, making it impossible to produce sufficiently energetic explosions (Hillebrandt & Niemeyer, 2000).

Another problem is that both pure detonation and pure deflagration models do not naturally reproduce the range in SN Ia properties, which trace a (nearly) single-parameter family, reflecting a roughly factor 5 range in the amount of ^{56}Ni that is synthesized

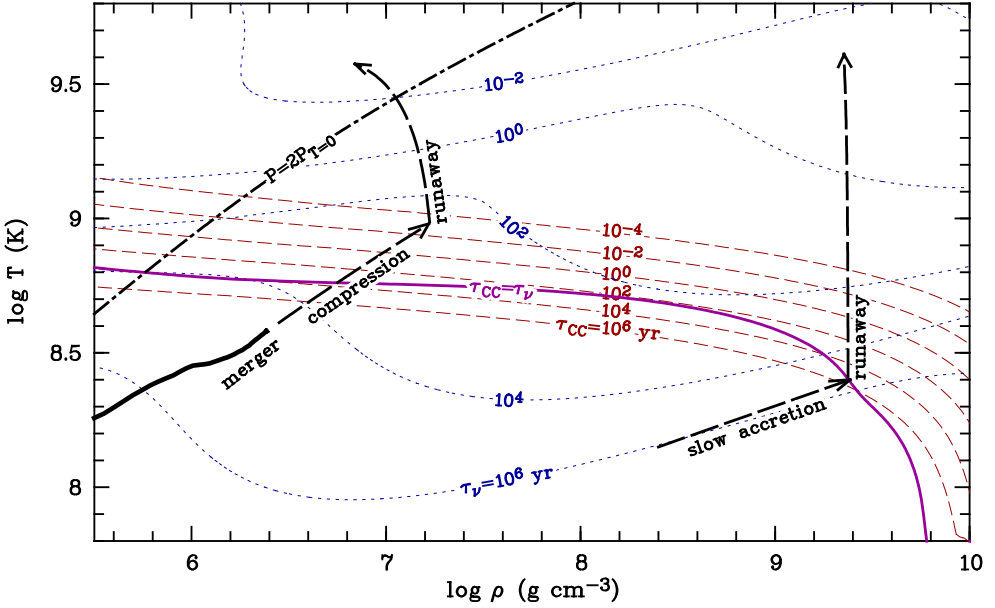


Figure 1. Temperature-density tracks leading to thermonuclear runaways. In the standard picture (on the right), a carbon-oxygen white dwarf accretes slowly, on a $\gtrsim 10^6$ yr timescale, and neutrino cooling keeps its internal temperature below a few 10^8 K (see the contours of constant cooling time τ_ν). When it approaches the Chandrasekhar limit and its central density rises dramatically, carbon fusion is ignited (where $\tau_{cc} = \tau_\nu$, i.e., the fusion heating time matches the neutrino cooling time), and – after 100–1000 yr of simmering – a thermal runaway ensues (at roughly constant pressure). In our alternative picture (van Kerkwijk *et al.*, 2010), a white dwarf merger leads to a rapidly rotating remnant with a temperature-density profile like that shown on the left (from Lorén-Aguilar *et al.* 2009, for a merger of two $0.6 M_\odot$ white dwarfs). This is initially not hot enough for ignition, but as the remnant disk accretes or the core spins down, the interior will be compressed and heated roughly adiabatically, until carbon fusion becomes faster than the accretion or spin-down timescales and the thermonuclear runaway starts (along a curved constant-pressure contour, as degeneracy is lifted).

(Phillips, 1993; Mazzali *et al.*, 2007). The above issues can be resolved with an *ad hoc* assumption, that an initial deflagration transitions into a detonation (Khokhlov, 1991). If so, the timing of the transition could determine how far the white dwarf expanded and thus how much ^{56}Ni was produced. Even with this assumption, however, it remains unclear why the outcome would depend on the population which the progenitor is in, i.e., why, as is observed, more luminous SN Ia preferentially occur in younger populations (Hamuy *et al.*, 1995; Sullivan *et al.*, 2010).

2. Sub-Chandrasekhar Mass Mergers as SN Ia Progenitors?

SN Ia could be understood more easily if they arose from sub-Chandrasekhar white dwarfs. Since for increasing mass, a larger fraction is dense enough to produce ^{56}Ni ($\rho \gtrsim 10^7 \text{ g cm}^{-3}$), a range of ^{56}Ni mass would be expected. Also, since more massive white dwarfs are the progeny of shorter-lived stars, younger populations should preferentially host luminous SN Ia. Encouragingly, pure detonations of white dwarfs with masses between 0.9 and $1.2 M_\odot$ reproduce the range in SN Ia properties, including, roughly,

their lightcurves and spectra (Shigeyama *et al.*, 1992; Sim *et al.*, 2010). Not clear yet, however, is whether the distribution in luminosity can also be matched easily.

The difficulty for sub-Chandrasekhar white dwarfs is to get them hot enough to ignite. To overcome neutrino losses, they have to be heated on a rather fast, $\lesssim 10^4$ yr timescale (see Fig. 1). One possibility is that carbon fusion is not triggered directly, but indirectly, by a detonation wave started by a thermonuclear runaway in a thick helium layer surrounding the core (Woosley & Weaver, 1994). These “double detonation” models, however, predict abundances in the outer ejecta – produced in the helium envelope – that are not seen in SN Ia (Hillebrandt & Niemeyer 2000; discussions continue about whether these effects can be reduced by helium layers that are thinner [Fink *et al.* 2010; Woosley & Kasen 2011] or have mixed in carbon [Kromer *et al.* 2010]). Another possibility is that fusion gets ignited during a merger that involves at least one massive, $\gtrsim 1 M_\odot$ white dwarf (Pakmor *et al.*, 2012). Those, however, have expected rates even lower than those of super-Chandrasekhar mergers, and thus likely are too rare.

Our alternative is that SN Ia result generally from mergers of carbon-oxygen white dwarfs, including those with sub-Chandrasekhar total mass (van Kerkwijk *et al.*, 2010). Both theoretical (*ibid.*) and empirical (Badenes & Maoz, 2012) rates are a factor three or so higher than near-Chandrasekhar rates, making them consistent with the SN Ia rate. Furthermore, the expected range in mass matches that for which detonations yield sufficient ^{56}Ni . The questions are whether fusion is ignited, and whether this triggers a detonation.

From simulations, the outcome of a white-dwarf merger depends strongly on whether the masses are similar (where “similar” is within $\sim 0.1 M_\odot$, Zhu *et al.* 2011; Zhu *et al.*, 2012, in preparation). If they are not, the remnant consists of an almost unaffected core of the more massive white dwarf, surrounded by a hot envelope of the disrupted lower-mass one. For these, further evolution likely leads to ignition at low density, stable burning, and, therefore, not to a SN Ia (see Shen *et al.* 2012).

For similar-mass white dwarfs, however, the remnants are hot throughout, and consist of rapidly rotating cores surrounded by thick, dense disks. Initially, the core is not hot enough to ignite fusion – nor dense enough to produce ^{56}Ni – but as the disk accretes or the remnants spins down (helped by, e.g., strong magnetic fields that could be generated in the strongly differentially rotating remnant), it will be compressed and heated further (see Fig. 1). The timescale would likely be the viscous one – hours to days – much faster than any relevant cooling timescale. An open question is where ignition takes place. If magnetic braking is important (as in a protostar or accreting pulsar), dissipation will be far from the remnant and ignition likely in the core. If accretion dominates, dissipative heating may lead to ignition in the outer regions (Shen *et al.*, 2012).

3. Observational Tests

It seems unlikely that the question of the nature of the progenitors of SN Ia will be resolved theoretically, and hence one has to turn to observational tests. So far, most have focussed on trying to distinguish between the single and double-degenerate scenario, with conflicting results: no signature of a (former) companion in early SN Ia lightcurves (Hayden *et al.*, 2010; Bianco *et al.*, 2011; Brown *et al.*, 2012; Bloom *et al.*, 2012) or in SN Ia remnants (e.g., Schaefer & Pagnotta 2012; Kerzendorf *et al.* 2012), yet evidence for circumstellar medium (Patat *et al.*, 2007; Sternberg *et al.*, 2011).

A different test would be to distinguish between a near or sub-Chandrasekhar mass. One clue is that in the near-Chandrasekhar case, where the explosion has to start with a deflagration, electron captures during this relatively slow phase are important, leading to the production of $\sim 0.1 M_{\odot}$ of stable iron-peak elements, much of which is ^{58}Ni (Maeda *et al.* 2010a, and references therein). In contrast, for sub-Chandrasekhar models, where the density is much lower and the explosion has to be a fast detonation, the only source of the neutrons required to produce stable iron-peak elements is ^{22}Ne . This is produced during helium burning (via $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(e^-, \nu_e)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$, where the ^{14}N is left by the CNO cycle), and wherever the temperatures become hot enough to produce ^{56}Ni , the excess neutrons end up mostly in ^{54}Fe and ^{58}Ni (Shigeyama *et al.*, 1992), with a mass of $\sim (58/14)X_{\text{CNO}} \simeq 4\%$ of the mass of ^{56}Ni ; hence, the mass of ^{58}Ni should be $\lesssim 0.02 M_{\odot}$ for a typical SN Ia with $0.6 M_{\odot}$ of ^{56}Ni .

Given the above, an observational test would be to look for evidence for a core dominated by stable elements. Arguably the most direct measurement of the amount of ^{58}Ni has been done from mid-infrared fine-structure lines in SN 2005df (in the nebular phase, when all ^{56}Ni has decayed; note that in other analyses often a near-Chandrasekhar explosion is assumed indirectly, e.g., in using the W7 model [e.g., Mazzali *et al.* 2007]). These yield an estimate of $\sim 0.01 M_{\odot}$ of nickel, which is much more consistent with a sub-Chandrasekhar model (Gerardy *et al.* 2007; note that these authors argued even this small mass was evidence for electron captures, but they did not consider the effect of ^{22}Ne). Similarly, the meteoritic abundance of nickel is $\sim 5\%$ that of iron (Cox, 2000), which is more easily understood in sub-Chandrasekhar models (as already noted in, e.g., Shigeyama *et al.* 1992; Nomoto *et al.* 1994).

In contrast, the presence of an inert, colder core is inferred from flat-topped line profiles (Motohara *et al.*, 2006). It is unclear, however, whether this cold core reflects a lack of heating, or rather enhanced cooling in an “infrared catastrophe” (Leloudas *et al.*, 2009). Evidence for an inert core comes also from differences in line profiles for lower and higher ionisation states (Maeda *et al.*, 2010b), differences that correlate with other SN Ia properties and are plausible for delayed detonation, near-Chandrasekhar models (Maeda *et al.*, 2010c). It is not yet known what to expect for sub-Chandrasekhar explosions, but nebular spectroscopy nevertheless seems one of the most promising ways of determining whether SN Ia result from near or sub-Chandrasekhar mass objects. Ideally, one would study supernovae that cover not only a range in SN Ia properties but also in host metallicity (with which ^{58}Ni should scale linearly for sub-Chandrasekhar models; for near-Chandrasekhar models, the dependence is more complicated, see, e.g., Jackson *et al.* 2010).

Acknowledgment

I thank Ken Nomoto and Kei’ichi Maeda for filling in many lacunae in my understanding of SN Ia and for pointing out to the importance of electron captures, Michael Lennox for help in researching the literature, Charles Zhu, Wolfgang Kerzendorf and Stuart Sim for discussions, and the referees for useful comments.

References

Badenes, C. & Maoz, D. 2012 The Merger Rate of Binary White Dwarfs in the Galactic

- Disk. *Astrophys. J.*, **749**, L11. (doi:10.1088/2041-8205/749/1/L11)
- Bianco, F. B. *et al.* 2011 Constraining Type Ia Supernovae Progenitors from Three Years of Supernova Legacy Survey Data. *Astrophys. J.*, **741**, 20. (doi:10.1088/0004-637X/741/1/20)
- Bloom, J. S. *et al.* 2012 A Compact Degenerate Primary-star Progenitor of SN 2011fe. *Astrophys. J.*, **744**, L17. (doi:10.1088/2041-8205/744/2/L17)
- Brown, P. J., Dawson, K. S., Harris, D. W., Olmstead, M., Milne, P. & Roming, P. W. A. 2012 Constraints on Type Ia Supernova Progenitor Companions from Early Ultraviolet Observations with Swift. *Astrophys. J.*, **749**, 18. (doi:10.1088/0004-637X/749/1/18)
- Cox, A. N. 2000 *Allen's astrophysical quantities*.
- Di Stefano, R. 2010a The Progenitors of Type Ia Supernovae. I. Are they Supersoft Sources? *Astrophys. J.*, **712**, 728–733. (doi:10.1088/0004-637X/712/1/728)
- Di Stefano, R. 2010b The Progenitors of Type Ia Supernovae. II. Are they Double-degenerate Binaries? The Symbiotic Channel. *Astrophys. J.*, **719**, 474–482. (doi:10.1088/0004-637X/719/1/474)
- Di Stefano, R., Voss, R. & Claeys, J. S. W. 2011 Spin-up/Spin-down Models for Type Ia Supernovae. *Astrophys. J.*, **738**, L1. (doi:10.1088/2041-8205/738/1/L1)
- Fink, M., Röpke, F. K., Hillebrandt, W., Seitenzahl, I. R., Sim, S. A. & Kromer, M. 2010 Double-detonation sub-Chandrasekhar supernovae: can minimum helium shell masses detonate the core? *Astron. Astrophys.*, **514**, A53. (doi:10.1051/0004-6361/200913892)
- Gerardy, C. L. *et al.* 2007 Signatures of Delayed Detonation, Asymmetry, and Electron Capture in the Mid-Infrared Spectra of Supernovae 2003hv and 2005df. *Astrophys. J.*, **661**, 995–1012. (doi:10.1086/516728)
- Gilfanov, M. & Bogdán, Á. 2010 An upper limit on the contribution of accreting white dwarfs to the typeIa supernova rate. *Nature*, **463**, 924–925. (doi:10.1038/nature08685)
- Hachisu, I., Kato, M. & Nomoto, K. 2010 Supersoft X-ray Phase of Single Degenerate Type Ia Supernova Progenitors in Early-type Galaxies. *Astrophys. J.*, **724**, L212–L216. (doi:10.1088/2041-8205/724/2/L212)
- Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A. & Aviles, R. 1995 A Hubble diagram of distant type IA supernovae. *Astron. J.*, **109**, 1–13. (doi:10.1086/117251)
- Hayden, B. T. *et al.* 2010 Single or Double Degenerate Progenitors? Searching for Shock Emission in the SDSS-II Type Ia Supernovae. *Astrophys. J.*, **722**, 1691–1698. (doi:10.1088/0004-637X/722/2/1691)
- Hillebrandt, W. & Niemeyer, J. C. 2000 Type IA Supernova Explosion Models. *Ann. Rev. Astron. Astrophys.*, **38**, 191–230. (doi:10.1146/annurev.astro.38.1.191)
- Iben, Jr., I. & Tutukov, A. V. 1984 Supernovae of type I as end products of the evolution of binaries with components of moderate initial mass (M not greater than about 9 solar masses). *Astrophys. J. Suppl. Ser.*, **54**, 335–372. (doi:10.1086/190932)
- Idan, I., Shaviv, N. J. & Shaviv, G. 2012 The Fate of a WD Accreting H-Rich Material at High Rates. *Journal of Physics Conference Series*, **337**(1), 012 051. (doi:10.1088/1742-6596/337/1/012051)
- Jackson, A. P., Calder, A. C., Townsley, D. M., Chamulak, D. A., Brown, E. F. & Timmes, F. X. 2010 Evaluating Systematic Dependencies of Type Ia Supernovae: The Influence of Deflagration to Detonation Density. *Astrophys. J.*, **720**, 99–113. (doi:10.1088/0004-637X/720/1/99)
- Justham, S. 2011 Single-degenerate Type Ia Supernovae Without Hydrogen Contamination. *Astrophys. J.*, **730**, L34. (doi:10.1088/2041-8205/730/2/L34)
- Kerzendorf, W. E., Schmidt, B. P., Laird, J. B., Podsiadlowski, P. & Bessell, M. S. 2012

- Hunting for the progenitor of SN 1006: High resolution spectroscopic search with the FLAMES instrument. *arXiv:1207.4481*.
- Khokhlov, A. M. 1991 Delayed detonation model for type IA supernovae. *Astron. Astrophys.*, **245**, 114–128.
- Kromer, M., Sim, S. A., Fink, M., Röpke, F. K., Seitenzahl, I. R. & Hillebrandt, W. 2010 Double-detonation Sub-Chandrasekhar Supernovae: Synthetic Observables for Minimum Helium Shell Mass Models. *Astrophys. J.*, **719**, 1067–1082. (doi:10.1088/0004-637X/719/2/1067)
- Leloudas, G. *et al.* 2009 The normal Type Ia SN 2003hv out to very late phases. *Astron. Astrophys.*, **505**, 265–279. (doi:10.1051/0004-6361/200912364)
- Lorén-Aguilar, P., Isern, J. & García-Berro, E. 2009 High-resolution smoothed particle hydrodynamics simulations of the merger of binary white dwarfs. *Astron. Astrophys.*, **500**, 1193–1205. (doi:10.1051/0004-6361/200811060)
- Maeda, K., Röpke, F. K., Fink, M., Hillebrandt, W., Travaglio, C. & Thielemann, F.-K. 2010a Nucleosynthesis in Two-Dimensional Delayed Detonation Models of Type Ia Supernova Explosions. *Astrophys. J.*, **712**, 624–638. (doi:10.1088/0004-637X/712/1/624)
- Maeda, K., Taubenberger, S., Sollerman, J., Mazzali, P. A., Leloudas, G., Nomoto, K. & Motohara, K. 2010b Nebular Spectra and Explosion Asymmetry of Type Ia Supernovae. *Astrophys. J.*, **708**, 1703–1715. (doi:10.1088/0004-637X/708/2/1703)
- Maeda, K. *et al.* 2010c An asymmetric explosion as the origin of spectral evolution diversity in type Ia supernovae. *Nature*, **466**, 82–85. (doi:10.1038/nature09122)
- Mannucci, F. *et al.* 2005 The supernova rate per unit mass. *Astron. Astrophys.*, **433**, 807–814. (doi:10.1051/0004-6361:20041411)
- Maoz, D., Mannucci, F., Li, W., Filippenko, A. V., Della Valle, M. & Panagia, N. 2011 Nearby supernova rates from the Lick Observatory Supernova Search - IV. A recovery method for the delay-time distribution. *Mon. Not. R. Astron. Soc.*, **412**, 1508–1521. (doi:10.1111/j.1365-2966.2010.16808.x)
- Mazzali, P. A., Röpke, F. K., Benetti, S. & Hillebrandt, W. 2007 A Common Explosion Mechanism for Type Ia Supernovae. *Science*, **315**, 825. (doi:10.1126/science.1136259)
- Mennekens, N., Vanbeveren, D., De Greve, J. P. & De Donder, E. 2010 The delay-time distribution of Type Ia supernovae: a comparison between theory and observation. *Astron. Astrophys.*, **515**, A89. (doi:10.1051/0004-6361/201014115)
- Motohara, K. *et al.* 2006 The Asymmetric Explosion of Type Ia Supernovae as Seen from Near-Infrared Observations. *Astrophys. J.*, **652**, L101–L104. (doi:10.1086/509919)
- Nomoto, K., Saio, H., Kato, M. & Hachisu, I. 2007 Thermal Stability of White Dwarfs Accreting Hydrogen-rich Matter and Progenitors of Type Ia Supernovae. *Astrophys. J.*, **663**, 1269–1276. (doi:10.1086/518465)
- Nomoto, K., Yamaoka, H., Shigeyama, T., Kumagai, S. & Tsujimoto, T. 1994 Type I supernovae and evolution of interacting binaries. In *Supernovae* (eds S. A. Bludman, R. Mochkovitch & J. Zinn-Justin), p. 199.
- Pakmor, R., Kromer, M., Taubenberger, S., Sim, S. A., Röpke, F. K. & Hillebrandt, W. 2012 Normal Type Ia Supernovae from Violent Mergers of White Dwarf Binaries. *Astrophys. J.*, **747**, L10. (doi:10.1088/2041-8205/747/1/L10)
- Patat, F. *et al.* 2007 Detection of Circumstellar Material in a Normal Type Ia Supernova. *Science*, **317**, 924. (doi:10.1126/science.1143005)
- Phillips, M. M. 1993 The absolute magnitudes of Type IA supernovae. *Astrophys. J.*, **413**, L105–L108. (doi:10.1086/186970)

- Pritchett, C. J., Howell, D. A. & Sullivan, M. 2008 The Progenitors of Type Ia Supernovae. *Astrophys. J.*, **683**, L25–L28. (doi:10.1086/591314)
- Rappaport, S., Di Stefano, R. & Smith, J. D. 1994 Formation and evolution of luminous supersoft X-ray sources. *Astrophys. J.*, **426**, 692–703. (doi:10.1086/174106)
- Ruiter, A. J., Belczynski, K. & Fryer, C. 2009 Rates and Delay Times of Type Ia Supernovae. *Astrophys. J.*, **699**, 2026–2036. (doi:10.1088/0004-637X/699/2/2026)
- Schaefer, B. E. & Pagnotta, A. 2012 An absence of ex-companion stars in the type Ia supernova remnant SNR 0509-67.5. *Nature*, **481**, 164–166. (doi:10.1038/nature10692)
- Seitenzahl, I. R., Meakin, C. A., Townsley, D. M., Lamb, D. Q. & Truran, J. W. 2009 Spontaneous Initiation of Detonations in White Dwarf Environments: Determination of Critical Sizes. *Astrophys. J.*, **696**, 515–527. (doi:10.1088/0004-637X/696/1/515)
- Shen, K. J., Bildsten, L., Kasen, D. & Quataert, E. 2012 The Long-term Evolution of Double White Dwarf Mergers. *Astrophys. J.*, **748**, 35. (doi:10.1088/0004-637X/748/1/35)
- Shigeyama, T., Nomoto, K., Yamaoka, H. & Thielemann, F.-K. 1992 Possible models for the type Ia supernova 1990N. *Astrophys. J.*, **386**, L13–L16. (doi:10.1086/186281)
- Sim, S. A. *et al.* 2010 Detonations in Sub-Chandrasekhar-mass C+O White Dwarfs. *Astrophys. J.*, **714**, L52–L57. (doi:10.1088/2041-8205/714/1/L52)
- Sternberg, A. *et al.* 2011 Circumstellar Material in Type Ia Supernovae via Sodium Absorption Features. *Science*, **333**, 856. (doi:10.1126/science.1203836)
- Sullivan, M. *et al.* 2010 The dependence of Type Ia Supernovae luminosities on their host galaxies. *Mon. Not. R. Astron. Soc.*, **406**, 782–802. (doi:10.1111/j.1365-2966.2010.16731.x)
- Townsley, D. M. & Bildsten, L. 2004 Theoretical Modeling of the Thermal State of Accreting White Dwarfs Undergoing Classical Nova Cycles. *Astrophys. J.*, **600**, 390–403. (doi:10.1086/379647)
- van Kerkwijk, M. H., Chang, P. & Justham, S. 2010 Sub-Chandrasekhar White Dwarf Mergers as the Progenitors of Type Ia Supernovae. *Astrophys. J.*, **722**, L157–L161. (doi:10.1088/2041-8205/722/2/L157)
- Webbink, R. F. 1984 Double white dwarfs as progenitors of R Coronae Borealis stars and Type I supernovae. *Astrophys. J.*, **277**, 355–360. (doi:10.1086/161701)
- Whelan, J. & Iben, Jr., I. 1973 Binaries and Supernovae of Type I. *Astrophys. J.*, **186**, 1007–1014. (doi:10.1086/152565)
- Woosley, S. E. & Kasen, D. 2011 Sub-Chandrasekhar Mass Models for Supernovae. *Astrophys. J.*, **734**, 38. (doi:10.1088/0004-637X/734/1/38)
- Woosley, S. E. & Weaver, T. A. 1994 Sub-Chandrasekhar mass models for Type Ia supernovae. *Astrophys. J.*, **423**, 371–379. (doi:10.1086/173813)
- Zhu, C., Chang, P., van Kerkwijk, M. & Wadsley, J. 2011 Properties of Carbon-Oxygen White Dwarf Merger Remnants. *arXiv:1109.4334*.
- Zorotovic, M., Schreiber, M. R. & Gänsicke, B. T. 2011 Post common envelope binaries from SDSS. XI. The white dwarf mass distributions of CVs and pre-CVs. *Astron. Astrophys.*, **536**, A42. (doi:10.1051/0004-6361/201116626)